Initial Results in the Development of a Guidance System for a Powered Wheelchair

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Abstract—**This paper describes the development of an automatically guided powered wheelchair for individuals with severe disabilities. The navigation and control of the wheelchair is based the accurate estimation of the location of the wheelchair within its operating workspace. A novel method used to generate and track reference paths which take the user to and from various destinations within the wheelchair's environment is presented. The paper also provides a qualitative description of the restrictions and requirements that are specific to the wheelchair application as well as the way in which the current system addresses these restrictions and requirements. Finally, actual experimental runs of the wheelchair system are presented.**

I. Introduction

FOR CERTAIN individuals with disabilities, the control of a powered wheelchair using traditional means (e.g., joystick, sip-and-puff devices) becomes prohibitively difficult or may be precluded altogether because of various environmental constraints, such as tight living quarters, or because of physical fatigue. To meet the challenge of assisting these individuals, a prototype wheelchair system is under development that allows a user with disabilities to navigate the wheelchair precisely and robustly from one location in the user's environment to another. The navigation and control of the wheelchair system presented in this paper is based on the methods developed for a general vision-based mobile-robot system [1]. For background purposes, this paper will describe briefly how the vision-based estimation and control methods for mobile robots are applied specifically to the powered wheelchair problem. However, the emphasis of the paper is on the difficulties associated with the challenge of operating a mobility device within the tight settings often associated with powered wheelchairs, such as office or home environments. The paper also presents experimental results obtained using a prototype system. In addition, a procedure for controlling the system's speed in order to ensure safe, accurate navigation is presented.

Recently, many researchers have turned their attention to producing automatic guidance systems that are able to assist users with the navigation of powered wheelchairs. For example, an autonomous wheelchair that follows guide tracks which are embedded in the floor has been recently developed [3]. While this approach is used readily in factory automation problems, the use of guide tracks may be impractical and difficult to implement and maintain due to the variety of complex paths that are required for household or office navigation and the need for an easily reconfigured system. An early work concerned with the development of an autonomous vehicle for individuals with disabilities is presented in [4]. This system uses vision and ultrasonic-based measurement devices to navigate throughout an office setting. Vision is used to verify the identity of known objects in the environment, while the ultrasonic system is used for obstacle avoidance and to orient the wheelchair relative to the walls of the environment for wall-following operations. More recently, various other wheelchair systems have been envisioned or built to provide an assistive navigation system [5]–[7] for persons with disabilities. These systems rely on accurate sensory information to assist the user in navigating along walls and/or avoiding obstacles. Issues related to the shared control of powered wheelchairs are also discussed in [8]–[11]. Generally, shared control systems aid the user by superseding the joint-level (i.e., joystick) control of the wheelchair under various circumstances. These circumstances occur when the system is in danger of striking an obstacle, when the user allows the wheelchair to follow a wall, or when the user desires to navigate through a doorway. These systems primarily use ultrasonic sensors to aid in the navigation of the wheelchair. However, the difficulties that are associated with the use of ultrasonic sensors for the wheelchair application have only recently been addressed (e.g., the problem of passing through doorways using sonar-based navigation [12]).

A unique approach to the development of an automatically guided powered wheelchair is presented in this paper. Unlike the systems mentioned above, the system described in this paper has the ability to estimate accurately the position and orientation of a wheelchair within its environment. Estimates of the wheelchair's position and orientation are produced by combining drive-wheel rotation information with the visual observations of small, passive "cues" that are within the wheelchair's operating region, typically on the walls and on other stationary objects. This basic capability of computing accurate position and orientation estimates allows for the circumvention of difficulties faced by the alternate approaches. For example, instead of following walls (which would be very difficult in a typical home or office setting where many objects are placed against the wall), reference paths which are used to guide the wheelchair user from one location within the user's environment to another are tracked by the wheelchair system.

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These reference paths may take the user through doorways and may approach solid objects (e.g., desks, tables, etc.). This approach of having the system track reference paths, which are stored in memory rather than physically placed on the floor, differentiates it from the wheelchair systems discussed above. The reference paths are physically "taught" to the system during a brief setup procedure. The estimates of the wheelchair's position and orientation during the teaching procedure are then used to generate a geometric representation of the taught reference path. When the system is called on to navigate along one of the taught reference paths, accurate estimates of the wheelchair's position and orientation are again computed. The errors between the current estimated position and orientation of the wheelchair and the reference path are calculated and are used to control the wheelchair in order to follow the reference path.

The system described in this paper incorporates task-level (or supervisory) control strategies for the wheelchair system, as opposed to shared control strategies adopted in [8]–[11]. Task-level control of the wheelchair allows the user to specify the desired task to be performed by the wheelchair system (e.g., "go to the kitchen table"). The desired task is chosen by the user by selecting the destination toward which the user wishes to proceed. Once the task is specified, the wheelchair system controls the chair in order to carry out the desired task. However, the user of the system retains supervisory control of the wheelchair at all times. As discussed later in the paper, the user can select the nominal speed of the wheelchair, stop and select a new destination, and/or stop and take over the navigation and control of the wheelchair at any time during motion. The user can also use the system to aid in the navigation of the wheelchair through difficult regions of operation, such as through doorways or when approaching solid objects. Shared control strategies, on the other hand, require user involvement at all times, and cannot complete any task without the assistance of the user.

It must be noted that this paper presents results from an early prototype. The authors do not claim to have addressed all the issues associated with an automatically guided wheelchair system for everyday use. The focus of this paper is the navigation (guidance) of the wheelchair, particularly the estimation and control of the system. Issues such as user interface, obstacle avoidance, battery usage, seating comfort, user demographics, etc., are not addressed here. Rather, it is hoped that the research discussed here will serve as the basis for a complete automatically guided wheelchair system, since such a system will not be successful without reliable, accurate navigation.

Section II provides a qualitative description of the special requirements and restrictions associated with the automatically guided powered wheelchair application and the way in which the system described in this paper addresses these requirements and restrictions. Brief descriptions of the algorithm used to produce the accurate position and orientation estimates and the methods used to teach and track desired reference paths are also presented in Section II. A complete description of these algorithms and methods can be found in [1]. In Section III, experimental results of the current system navigating within a cluttered laboratory environment are presented, along with results which show that estimation accuracy can be increased by controlling the translational speed of the wheelchair. Section IV discusses areas for further work and provides some concluding remarks.

II. The Wheelchair Application

A. Requirements and Restrictions

The general navigation problem for mobile robots has proven to be a very difficult problem to solve. The wheelchair application, however, adds further difficulty to the problem due to several special requirements. These requirements stem from the fact that the system is used to assist an individual in his or her daily tasks, as opposed to other mobile robot systems which are used for material handling, sentry, or hazardous-environment operations. Some of the special requirements for the wheelchair application are outlined below. This list is not meant to order or rank the relative importance of any of these requirements.

The first special requirement is that the system must be more accurate than typical mobile robots (see Section III for a discussion of accuracy requirements and measures). For a mobile robot system operating on a wide-open factory floor, errors of several inches may well be acceptable. However, when dealing with tight-tolerance paths in a home or office (e.g., passing through a doorway or approaching a desk), a few inches can be the difference between the successful completion of the task and disaster. This actually requires two types of accuracy: accuracy in path-tracking and accuracy in location. In other words, the system could fail despite "realizing" that it is far from the nominal path (path-tracking error), or by mistakenly "thinking" that it is on the nominal path due to poor estimates of the current pose of the vehicle (location error), or it could fail due to some combination of these two inaccuracies. Therefore, for a wheelchair system to be successful, accuracy must be maintained both in estimating the current pose of the system, and in tracking a given path.

Second, the system must be robust and repeatable. It must be able to maneuver accurately every time it is used, despite the shifting weight of the user, changes in operating conditions, and even minor changes in the system itself (less battery power, slight deformations in the wheels, etc.). Furthermore, the system must be able to deal with external disturbances, such as being displaced from its nominal position, running over various surfaces (carpet, tile, etc.), and even running over small objects (power cords, floor mats, rugs). This requires robustness in all phases of the navigation problem. Accurate estimates of the wheelchair's pose must be maintained, despite imperfections in the model of the system and variability of measurements since it is extremely unlikely that the same series of measurements will occur more than once. In the path-generation phase of the navigation problem, it is necessary to plan paths which are, in some sense, robust. For example, the paths should not go through a doorway very near to the frame, since a small tracking error would result in a collision. Recently, researchers have begun examining the possibility of

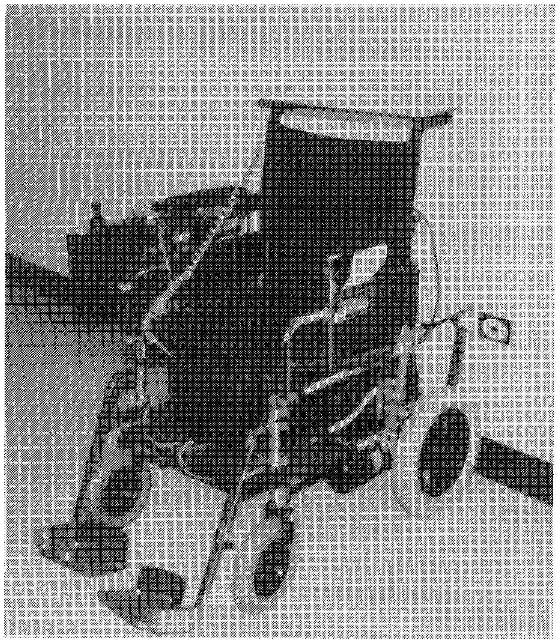

Fig. 1. Experimental wheelchair system.

planning such paths [16], [17], which can be followed safely despite inaccuracies in pose estimates or path tracking. Finally, in the path-tracking phase, the wheelchair system must be able to recover from disturbances and still track the remainder of the path accurately.

The third special requirement imposed by the wheelchair application is that of a smooth (that is, low in-plane accelerations) ride to ensure user comfort. Again, for material delivery applications (food, mail, parts, etc.), it is not often critical to have an especially smooth ride, and large accelerations may be allowable, especially since special compartments are often designed for holding the cargo. For a human user, however, a smooth (e.g., low acceleration) ride must be ensured for user comfort and safety. The path-tracking algorithm must accommodate this need while still accurately following the path.

Fourth, the system should be simple and relatively inexpensive to set up, to maintain, and to use. For a wheelchair system to be practical, it cannot be so complicated that specialists are needed for months of setup and training every time a minor change is required. Both for practicality and for cost, an aide (nurse, relative, etc.) should be able to provide most of the assistance, if any is needed. Furthermore, the system should be adaptable to a variety of powered wheelchair platforms and user interfaces.

Finally, it must be remembered that the passenger is a human being. In addition to the requirement of physical comfort described in the third special requirement, the system should function as an assist to the user, not as a caretaker [18]. The user should always have supervisory control over the system and should always be able to override the automatic control mode at any time, especially retaining the ability to stop the wheelchair's motion. Furthermore, the user should be able to adjust the system performance in real time.

The development of the automatically-guided wheelchair described in this paper has been conducted in order to address the requirements and restrictions mentioned above. The approach outlined in the following subsection describes how the current prototype system provides a workable solution to the wheelchair navigation problem. This prototype wheelchair system is shown in Fig. 1. For a detailed description of how the wheelchair system addresses each of these special requirements, see [19].

B. Approach

The precise navigation and control of the wheelchair system is predicated on computing accurate estimates of the wheelchair's pose (i.e., position (X, Y) and orientation ϕ) within its operating environment. This is accomplished through a novel application of the extended Kalman filter algorithm which is used to combine odometry (wheel rotation) information with external vision-based observations of the surrounding environment [1]. The extended Kalman filter then produces optimal estimates of the wheelchair's pose provided that the disturbances to the system and the observation or measurement noise are modeled by Gaussian distributed white noise processes.

A set of differential equations which relate wheel motion to the position and orientation of the wheelchair are numerically integrated to produce the so-called "dead-reckoned" estimates of the wheelchair's pose [1]. The wheel motion is sensed using optical encoders which are mounted on the wheelchair and allowed to roll on the two drive wheels. However, pose estimates which are based on odometry (dead-reckoning) information alone will be in error as the wheelchair moves throughout its environment due to modeling errors, wheel slippage, numerical integration errors, and inaccurate initial conditions. Therefore, external observations which are related to the wheelchair's pose are used to correct and update the position and orientation estimates via the extended Kalman filter algorithm. The vision-based observation of small "cues" placed throughout the wheelchair's surrounding environment is used for the wheelchair system described in this paper. The location of a cue in the image-plane of a camera mounted on the wheelchair is algebraically related to the wheelchair's pose [1]. Two cameras are mounted below the seat of the wheelchair and positioned so that each camera views a large portion of the wheelchair's environment. The cameras are also positioned so that each camera's view is not blocked by the user's lower extremities. A schematic of the placement of these video cameras on the wheelchair is shown in Fig. 2.

The image-plane observation of a cue by itself does not provide enough information to solve for the wheelchair's pose, but instead provides an independent measurement that is used to correct the errors that accumulate in the dead-reckoned pose estimates. Note that the only *a priori* information given to the system for estimation purposes is the physical location of the visual cues placed within the wheelchair's surrounding environment. Therefore, a complete map of the environment is neither used nor required. Also note that the estimates of the wheelchair's pose can be generated at all times regardless of

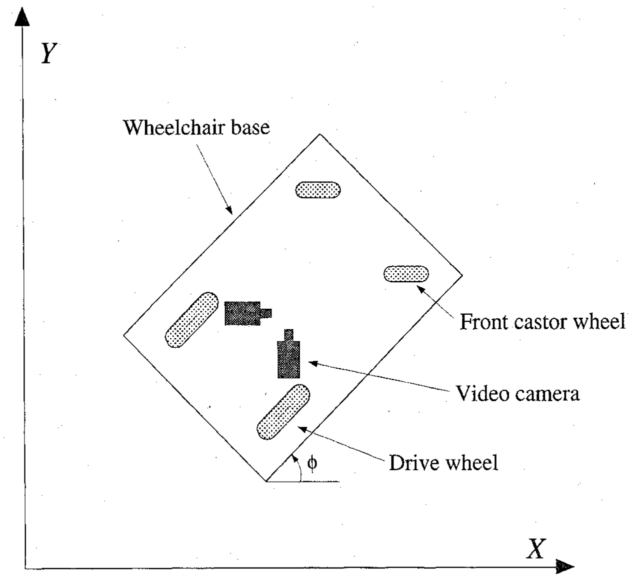

Fig. 2. Wheelchair schematic.

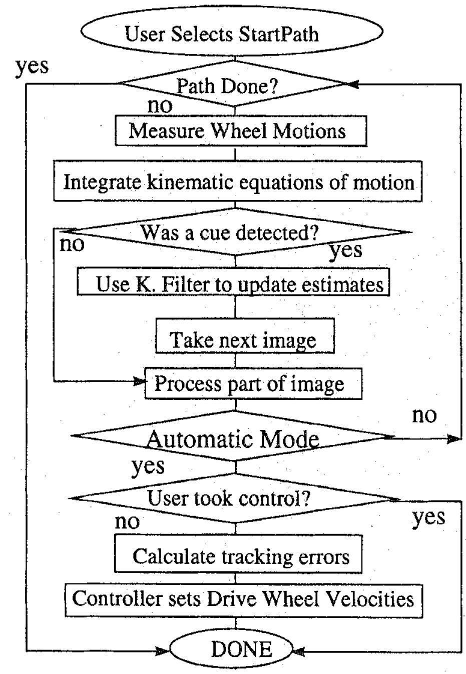

Fig. 3. Wheelchair system guidance flowchart.

the wheelchair's mode of operation (manual control or fully automatic control).

The automatic guidance of the wheelchair is carried out through a "teach-repeat" procedure, whereby paths which take the wheelchair user from location to location are taught by manually leading the chair through the path of interest. The estimation algorithm described above is used to create a compact representation of these taught reference paths. A number of paths would be taught to the system during a one-time teaching session and stored for future playback. The path is then tracked by controlling the differential speed between the two wheelchair drive wheels. The entire guidance and control algorithm is developed to be independent of time in part so that the translational speed of the wheelchair can be modified without affecting the path-tracking algorithm.

The advantages of controlling the translational speed of the wheelchair independent from the path-tracking algorithm will be illustrated in Section III-B. In general terms, however, a slow wheelchair speed will result in an increase in the accuracy of the wheelchair's pose estimates and will improve the path-tracking performance. This is due to the fact that, at slow speeds, more cues can be observed per distance traveled and, therefore, the dead-reckoning errors will tend not to accumulate. With regard to path tracking, a slow wheelchair speed will give the system the opportunity to follow closely the reference path in regions of high path curvature. In regions where the path has little curvature (i.e., straight line-paths) or where tracking accuracy is not crucial (e.g., proceeding down a wide hallway), the speed of the wheelchair can be increased without sacrificing safety.

Fig. 3 is a simplified flowchart describing the general operation of the system guidance algorithm. Note that no action is taken until the user requests that the system start following a path. Also, the system checks to see if the user wants to resume normal operation every time through the cycle before automatically controlling the wheelchair. Also note that the system functions even if no visual information is available (though estimate accuracy will suffer if no information is available), and that, because of processor speed limitations, the system does not process the entire image at once. For further details of the development of the estimation and control algorithms used by this system, the reader is referred to [1].

The approach outlined above has been realized by retrofitting an Everest and Jennings Tempest powered wheelchair with a 386-based personal computer, two black and white 512 by 480 pixel CCD video cameras, two 1000 count-per-revolution optical encoders mounted on the drive wheels, and an additional battery to run the computer. During the automatic guidance of the system, the drive wheels are controlled directly through the existing wheelchair motor controller box which is nominally attached to the joystick. A switch has been installed so that the wheelchair can be navigated by the joystick alone or by the estimation and control methods described in this section. In addition, the wheelchair's standard power on/off button may be used to stop the system at any time.

III. Experimental Results and Speed Control

A. Results

The automatically guided wheelchair system has been tested over a broad range of paths and within a variety of environments. These tests have been run in home, office, classroom, and laboratory settings. They have included a variety of loads carried in the wheelchair's seat, ranging from nothing, to a computer, to a 200-lb human passenger. In addition, the system has been run on various floor surfaces, from smooth poured concrete, to tile, to a variety of carpet types.

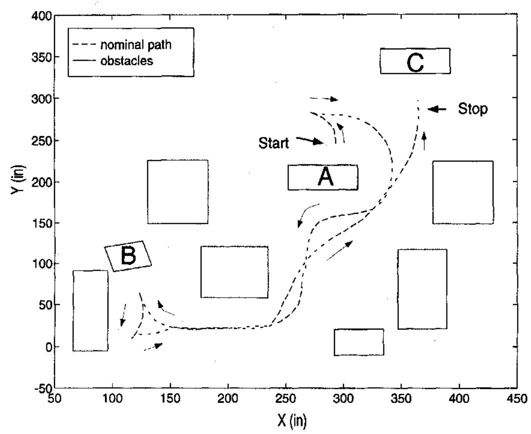

Fig. 4. Room layout with nominal path.

This section will present some experimental results obtained from the wheelchair system while tracking a specific reference path. The reference, or nominal, path was taught in the Mechanical Systems and Robotics Laboratory at the University of Notre Dame. This room is large (approximately 1300 square feet) and contains several desks which served as starting points and destinations for the wheelchair. The laboratory environment also contains various other fixed objects which served as obstacles. Recall that for the navigation of the wheelchair, visual cues must be placed throughout the wheelchair's environment. For the experimental runs shown in this section, 16 cues were spread about the laboratory. The physical locations of these 16 cues are the only *a priori* information given to the system before teaching.

The layout of the room, along with a plot of the reference or nominal path which was taught to the wheelchair, is shown in Fig. 4. The wheelchair was taught according to the approach described in Section II-B. Note that the objects mapped in Fig. 4 are shown for viewing purposes only. The locations of these objects are unknown to the wheelchair system, as this system does not rely on any map of the environment for navigation purposes. Instead, as stated above, only the locations of the 16 visual cues are known to the wheelchair system. The taught (or nominal) path begins at the desk marked "Desk A" in Fig. 4. The system then backs away from Desk A, crosses the room, and approaches and stops at the desk marked Desk B. Finally, the wheelchair backs away from Desk B and crosses the room again to approach and stop at the desk marked Desk C. Recall that this nominal path is taught by an individual leading the wheelchair system along the desired path. The nominal path is free from obstacles because the individual teaching the nominal path avoided the obstacles within the room. Likewise, the position and orientation of the wheelchair relative to Desks A, B, and C is determined by the teacher. The floor surface for this path is a combination of poured concrete and carpeting.

Note that no method of directly measuring the paths taught or tracked by the wheelchair is generally available. This is, after all, why the estimation algorithm described in Section II is required. Therefore, the path shown in Fig. 4 and in subsequent figures are actually a trace of the estimated path of the wheelchair as produced by the extended Kalman filter algorithm presented in Section II-B. Also note that the position estimates of a point on the back of the wheelchair are recorded during the teaching of the nominal path. For example, in Fig. 4, while the nominal path stops more than a foot short of the destination marked "Desk C", the front of the wheelchair approaches within inches of Desk C.

Some further discussion of system accuracy is warranted before results are presented. As stated in Section II, a wheelchair system will generally require more accuracy than other types of mobile robots. Exactly how accurate the system must be, however, will clearly depend on the environment and the taught trajectory. For example, when going through a doorway, the prototype wheelchair system is 26 inches wide at its widest point and standard door widths are 32 or 36 inches, meaning that the system must be accurate to within three or five inches (depending on the door width) *if the reference path is taught down the exact middle of the doorway and perfectly straight.* Since this is impossible to guarantee, and the wheelchair must often be turning as it passes through the doorway, the accuracy should really be better than the three inches stated above. Note that approaching a desk requires accuracy in two directions, in that the wheelchair must be close enough to use the desk without hitting it (which for our system requires stopping within four inches of the desk, requiring accuracy of plus or minus two inches if the path is taught correctly), but it must also place the user's feet under the desk between the desk's legs (for the prototype, the footrests are 18 inches wide, the legs of the desk are 24 inches apart, so again the system must be accurate within three inches if the path is taught perfectly). In general, as long as the system can consistently follow a path without colliding with any obstacle, reaching all the desired destinations, it is deemed to be accurate enough. For a discussion of additional means of verifying system accuracy, see Section III-B. For more information on controlling the wheelchair in order to maintain direction-specific accuracy requirements, see [19].

Once the nominal reference path is taught to the wheelchair, the system can then track or follow this nominal path. All of the experimental runs presented in this paper were executed with a human passenger (one of the authors). The wheelchair is placed approximately in the starting location in front of Desk A and the computer navigation and control of the wheelchair begins. A plot of the path tracked by the wheelchair while following the nominal path is shown in Fig. 5. This figure shows that the wheelchair follows the nominal path to each of the desired destinations, Desks B and C. At each desk, the wheelchair system pauses and waits for the human passenger to indicate when to back away from the desk and proceed toward the next desired destination. Also shown in Fig. 5 is a representation of the wheelchair when stopped at Desk B. This representation shows that the front of the wheelchair approaches within inches of the desk without making contact. In this figure, the wheelchair is drawn to scale and the footrests are not shown since they move under the desk as the chair comes to rest in front of the desk.

Also, Fig. 5 shows that there are occasional "jumps" in the estimates of the tracked path. These jumps occur when the ex-

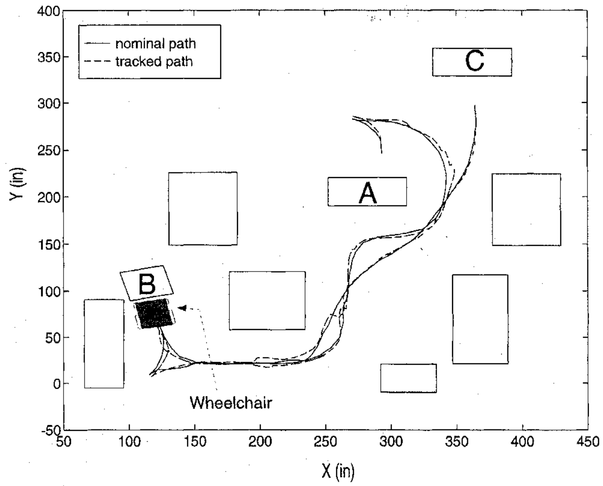

Fig. 5. Tracking of the nominal path.

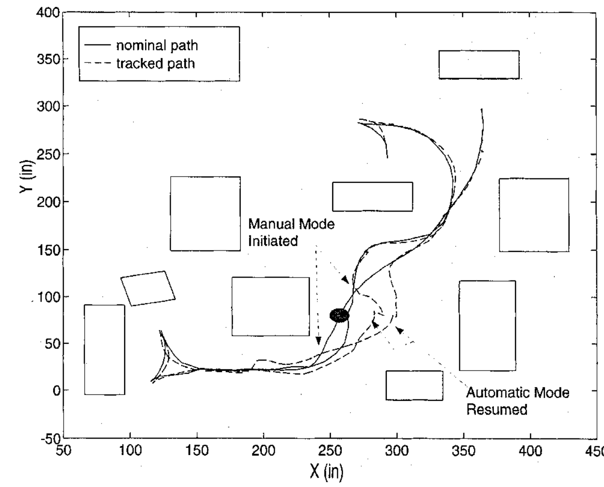

Fig. 6. Tracking of the nominal path with manual obstacle avoidance.

tended Kalman filter updates the estimates of the wheelchair's position and orientation after traveling significant distances with no observations of the visual cues. This situation may occur when the line of sight of both video cameras mounted on the wheelchair becomes obstructed by objects in the environment. Note, however, that despite these large disturbances, the system quickly returns to the reference path. It should also be noted that these jumps in the estimated tracked path do *not* result in jumps in the actual tracked path. The control gains are set in order to bring the system back to the nominal path smoothly and quickly, despite these disturbances in the estimates. The total time taken for the system to track this path was approximately 175 s, including the intermediate stop at Desk B. This results in an average tracking speed of 0.5 ft/s.

Although there is currently no automatic obstacle avoidance built into the system, the user can take over direct control of the system at any time and disengage the automatic-guidance of the wheelchair. To demonstrate this, a trash can was placed in the room, in a location where it would interfere with the nominal path both in going to Desk B and in returning to Desk C as shown in Fig. 6. Then, while tracking the path, the wheelchair user took control of the system to maneuver around the obstacle, and then engaged the automatic guidance of the system and continued tracking toward Desk B. Similarly, on the way back to Desk C, the user manually avoided the obstacle and then engaged the automatic guidance of the wheelchair to return to Desk C. Notice that the system returns to the reference path smoothly and quickly after being returned to automatic mode, despite being several feet from the reference path. Eventually, the system will be modified to allow for automatic avoidance of obstacles that may be placed in the way of one of the taught reference paths. As shown in Fig. 6, the current system demonstrates that the current navigation and control algorithms would work well with an added module for obstacle avoidance.

B. Speed Control

In order to test system accuracy and the assertion that slowing the wheelchair will improve estimate accuracy, the vehicle tracked the taught path (shown in Fig. 4) ten consecutive times, succeeding every time in approaching the desks accurately. The fact that it accomplished this without running into either desk or any of the obstacles indicates that the navigation is accurate enough to complete this trajectory (see previous section). But how can one quantify the accuracy of the performance of the system as well as that of the estimates? To answer this question, the final position of a point on the vehicle was marked on the floor in each of these ten runs. The physical location of these marks could then be compared to the estimated final positions. Unfortunately, this would not provide a true measure of the accuracy of the system in tracking paths, even if the absolute positions of these marks could be measured perfectly. It must be remembered that the estimated pose is determined, in some sense, relative to the cues. This is actually a strength of the system, since the system can function well even if there are significant errors in the placement of the cues. This means that the system may, in fact, be following the taught path precisely, even though the global estimates are somewhat inaccurate (if the cues are placed inaccurately).

In order to get a better picture of the accuracy of the position estimates then, it was assumed that the mean of the estimated position would correspond to the mean of the actual positions. Although this assumption may not be entirely correct (statistically, it would be true as the number of runs became very large given the assumptions made by the Kalman Filter), it allows meaningful *comparisons* of accuracy to be made regardless of the absolute accuracy. The final positions (measured versus estimated) are plotted in Fig. 7. The final position of each run of the system is marked by the number of that run, ranging from 0 to 9. The underlined numbers represent the measured positions, while the plain numbers represent the estimates. Note that the area enclosed by the plot represents a 5×5 inch area.

Several things are worth noting in Fig. 7. In general, we note that the estimates are at least close to the measured positions and the system has proven somewhat repeatable (since all the positions are located within the 5×5 inch area of the plot). However, there is a significant deviation

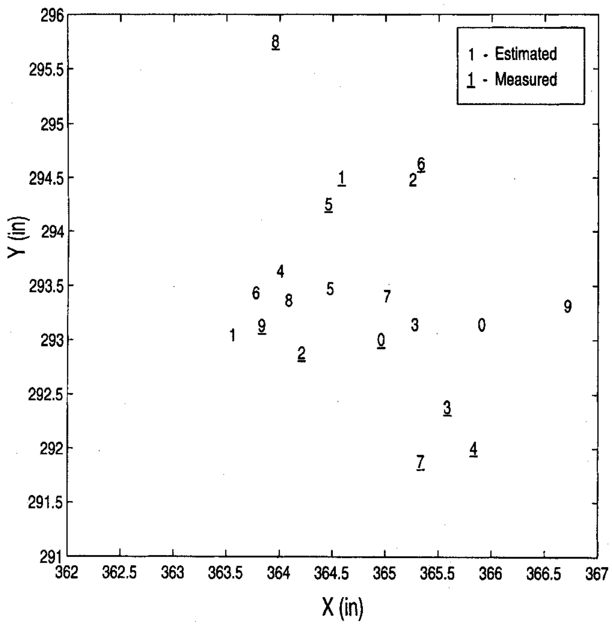

Fig. 7. Comparison of actual and estimated positions—higher final speed.

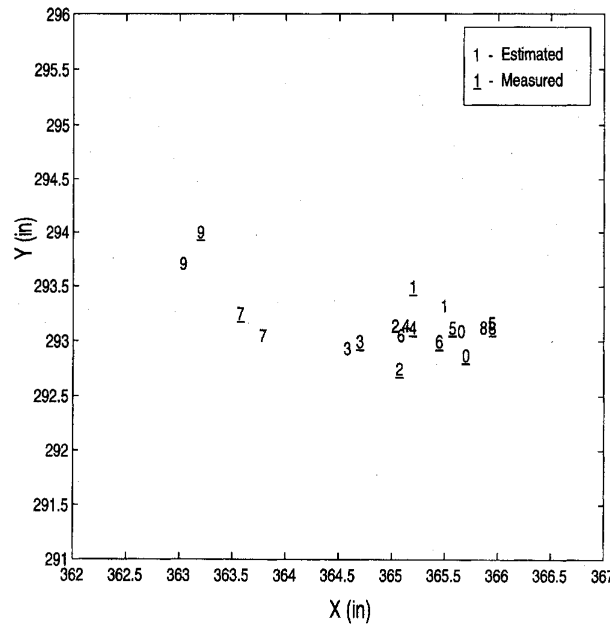

Fig. 8. Comparison of actual and estimated positions—slower final speed.

in the actual measured positions (standard deviation in the X direction was 0.7 inches, 1.3 inches in the Y direction), and in the difference between actual and estimated positions (quantitative data will be presented in a comparison below). For example, in some cases (such as runs 0 and 3) the measurements and estimates are about an inch apart (0.96 and 0.82 inches, respectively), while for other runs (notably 9), the measurements and estimates are much further apart (2.89 inches). This graph allows the reader to differentiate *following error*, which is the error between the estimated and reference pose, from *estimation error*, which is the error between the estimated and actual pose. To explain this point, it must be recalled that the total error is the vector sum of these two errors. In terms of Fig. 7, if the following error were zero with a finite estimation error, in each case the estimated final position would be exactly the same (i.e., 1, 2, $\cdots$, 9 are all at the same location), but the actual final positions would vary. If the estimation error were zero with a finite following error, in each case the measured and estimated positions would equal each other (e.g., 1 and $\underline{1}$ would lie on top of one another), but would not be the same from one run to the next. It is clear from this plot that there are both types of errors: the final estimated positions vary, and they do not agree perfectly with the final measured positions.

To investigate whether reducing the speed has any effect on the estimation error, the same reference path was tracked again. However, in this case, the wheelchair's reference speed was reduced to an average of 40% of the nominal value for the last ten segments (8 ft) of the trajectory (for the rest of the trajectory, however, the same speed was used in both cases). Again, ten consecutive runs were conducted and all were completed successfully. The results of these runs are plotted in Fig. 8. Several differences are immediately apparent between the two cases. It is clear from this figure that reducing the reference speed has accomplished the desired result by reducing the estimation error. In this figure, the measured and estimated final positions are always close to one another. Another interesting result is that the slower speed has reduced the following error, particularly in the Y direction (in which the standard deviation of the measured positions dropped to 0.35 inches). This is not unexpected, since the lower speed will allow the wheelchair to stop more precisely due to the decreased importance of dynamic effects.

TABLE I
COMPARISON OF EXPERIMENTAL TRIALS FOR TWO SPEED LEVELS

	Average X error (in)	Average Y error (in)	Maximum X error (in)	Maximum Y error (in)
Nominal speed	1.006	1.167	2.884	2.393
Low speed	0.175	0.146	0.369	0.393

To continue the comparisons, the data from the ten runs using both speed levels were further analyzed. An estimation error (the difference between the actual and estimated final position) in each direction was calculated for each case. The average and worst-case errors were then determined. The results of these comparisons are shown in Table I. Here we can clearly see that slowing the wheelchair has had precisely the desired effect: estimate accuracy has improved, with average and maximum estimate errors having been reduced to approximately one-sixth of their values for the case in which the nominal speed was used. This indicates that the strategy of slowing the system when higher accuracy is required is a promising one. It should also be noted here that a similar increase in accuracy can be expected by speeding up the computing hardware, as this has essentially the same effect: more information can be brought into the system per unit distance traveled.

These tests involve measuring only the endpoint of the trajectory. As stated above, the actual accuracy during motion is difficult or impossible to measure precisely. However, two points must be made. First, as indicated earlier, there is some measure of the accuracy of the system in that it was able to successfully reach the desired destinations without any collisions for 20 consecutive runs. Furthermore, any point along the path could be made the endpoint, and the accuracy measured there in a manner similar to that described above. Generally, the results of such tests would be expected to agree with the above results, *given similar tracking speeds* (average of 0.5 ft/s as described above) *and cue density* (a total of four cues were available for the last eight feet of the path). Note, however, that due to observability considerations, the relative position and orientation of the wheelchair, and the cues will also play a role in determining the accuracy. This relationship was in no way optimized for the tests described above, so the results presented here are expected to be typical.

IV. Discussion and Conclusions

This paper describes the development of an automatically guided wheelchair system for individuals with severe disabilities. The wheelchair system has been demonstrated following a variety of paths in different operating environments (a lab, an office, a classroom, and an apartment setting) since 1992. Recently, the configuration of the components added to the wheelchair was modified in order to accommodate a human rider. The system has proven robust enough to track paths accurately when there is no passenger, as well as when carrying a 200-lb rider. The wheelchair user maintains supervisory control of the system at all times. This paper has described the particular challenges the wheelchair application poses to the solution of the general navigation problem. The paper has also presented experimental results of the system for the first time.

The automatically guided wheelchair works robustly and accurately due to the novel manner in which it solves the navigation problem. The extended Kalman filter accurately estimates the system's pose (position and orientation) in the environment and solves the location problem by combining the measured wheel rotations of the chair along with observations of passive, visual beacons (cues). The path-generation problem is solved using a teach-repeat mode, allowing the system to function without the need for a detailed representation of the room. This method also allows the teacher's experience to be used in teaching the nominal paths, and minimizes the effects of any errors in the placement of the beacons. Finally, the path-tracking problem is solved using a PID control algorithm and a geometric path description which is used to compute tracking errors. This results in the path-tracking algorithm being robust to large disturbances and allows the speed to be adjusted in real-time without altering the path tracking algorithm. It should be noted that this approach is quite different from the shared-control systems which many researchers are working with. It must also be noted that the work described in this paper concentrates on navigation (guidance) of a powered wheelchair and is only a step in the process of producing a viable automatically guided wheelchair system for everyday use.

Clearly, work remains to be done to improve the existing system. First, an obstacle-avoidance strategy must be developed. Since the system can easily switch out of the path-tracking mode and into the obstacle-avoidance mode and back as shown in Fig. 6, it is felt that an existing obstacle-avoidance strategy, for example, as suggested by [7], could be integrated into the existing automatically guided wheelchair system. Clearly, processing speeds and hardware may need to change to accommodate such a system, but the current algorithms should allow for simple integration with the current estimation and control capablities. Furthermore, the development of obstacle-avoidance strategies would lead to a further advantage in the teach-repeat mode of operation, since the system could compare sonar maps obtained during teaching to those available while tracking. Therefore, only new sonar readings would constitute obstacles to be avoided. This methodology could be used in order to solve the problem of distinguishing obstacles from other solid objects in the room. Finally, the addition of this sonar information could easily be used by the automatically-guided wheelchair system in order to define the acceptable error at different regions of the path. When the system is near solid objects, it must be more accurate, while the system requires less accuracy in wide open spaces. This could be accomplished using the methodology described in [20].

Another area to be explored further deals with the user interface. A modular, easy-to-use interface must be developed which can connect directly to a variety of input devices (joystick, sip-puff, etc.). Currently, the authors are working with individuals from Hines VA to allow development of such an interface. Additionally, efforts to standardize controllers and input devices have increased recently and would greatly simplify the task of implementing this user interface on a variety of platforms. Clinical testing and evaluation of the system described in this paper is also planned in the near future. Feedback from these clinical tests will then be used to improve the system. A Hines VA-funded survey is underway in order to identify the types of individual users who would benefit most from such a system, and how many such users there are in different rehabilitation settings.

In addition to these major tasks, several smaller tasks remain. The computer must be upgraded and downsized (currently a full-size 386-based personal computer is attached to the back of the chair). The electrical power used by the computer and cameras should be drawn from the wheelchair's batteries, rather than having a separate power source. Bumper switches should be added in order to ensure safety, and finally, the image-analysis routine should be altered to detect naturally occurring cues such as corners, doors, and/or wall outlets.

Although some work remains to bring the wheelchair system to the point where clinical tests can be performed, the methods presented in this paper demonstrate that the development of an automatically guided powered wheelchair is feasible. It is hoped that this system will provide the user with the capability, which might not be otherwise available, to navigate accurately throughout various operating environments. Therefore, through the use of the automatically guided powered wheelchair, there will be a decreased dependence on the use of a caretaker to perform some routine tasks and the mobility and independence of individuals with disabilities will be enhanced.

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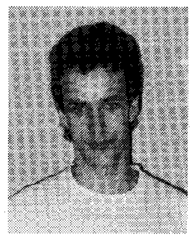

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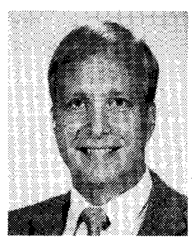

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